

STRUCTURAL TRANSITION IN THE NGC 6251 JET: AN INTERPLAY WITH THE SUPERMASSIVE BLACK HOLE AND ITS HOST GALAXY

CHIH-YIN TSENG^{1,2}, KEIICHI ASADA¹, MASANORI NAKAMURA¹,
HUNG-YI PU¹, JUAN-CARLOS ALGABA^{1,3}, AND WEN-PING LO^{1,2}

¹Institute of Astronomy & Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617, Taiwan

²Department of Physics, National Taiwan University, Taipei 10617, Taiwan

³Korea Astronomy and Space Science Institute, 776, Daedeokdae-ro, Yuseong-gu, Daejeon, 305-348, Korea

ABSTRACT

The structure of the NGC 6251 jet at the milliarcsecond scale is investigated using the images taken with the European VLBI Network and the Very Long Baseline Array. We detect a structural transition of the jet from a parabolic to a conical shape at a distance of $(1-2) \times 10^5$ times the Schwarzschild radius from the central engine, which is close to the sphere of gravitational influence (SGI) of the supermassive black hole (SMBH). We also examine the jet pressure profiles with the synchrotron minimum energy assumption to discuss the physical origin of the structural transition. The NGC 6251 jet, together with the M 87 jet, suggests a fundamental process of the structural transition in active galactic nuclei (AGN) jets. The collimated AGN jets are characterized by their external galactic medium, showing that AGN jets interplay with the SMBH and its host galaxy.

Keywords: galaxies: active - galaxies: individual: NGC 6251 - galaxies: jets - radio continuum: galaxies

1. INTRODUCTION

The collimation mechanism of jets from active galactic nuclei (AGN) remains one of the open questions in high energy astrophysics. Structural studies of the jet in the collimation zone, which requires an imaging in (sub-)milliarcsecond resolution, have been uniquely provided by Very Long Baseline Interferometry (VLBI). It has been found that some of the jets in the nearby sources are gradually collimated on pc scales (e.g., M 87: [Asada & Nakamura 2012](#), hereafter AN12; 3C 84: [Nagai et al. 2014](#); Cyg A: [Boccardi et al. 2016](#)), while the majority of distant blazar jets exhibit (freely expanding) conical shape on the scale beyond ~ 10 pc (e.g., [Jorstad et al. 2005](#); [Pushkarev et al. 2014](#)). Magnetohydrodynamic (MHD) processes are often invoked to explain their collimation together with acceleration properties ([Meier et al. 2001](#)). In principle, the bulk acceleration of MHD jets takes place in a parabolic stream ([Beskin & Nokhrina 2006](#); [Komissarov et al. 2007](#); [Lyubarsky 2009](#)). Nevertheless, it is unclear whether the external confinement by the environment plays a crucial role, or self-collimation by the toroidal magnetic field (i.e., hoop stress) alone can be responsible; the latter mechanism is most likely for non-relativistic jets (e.g., young stellar object jets, [Contopoulos et al. 2015](#)).

Recent observations of M 87 has found that the structural transition of the jet from a parabolic to conical

shape takes place at around the Bondi accretion radius, the outermost extent of the gravitational influence upon ambient gas by the supermassive black hole (SMBH), suggesting that the AGN jet collimation is subject to thermal confinement by the stratified interstellar medium (ISM) ([AN12](#); [Nakamura & Asada 2013](#), hereafter NA13). Interestingly, the simultaneity of gradual acceleration and collimation are also detected in the M 87 jet with VLBI monitoring observations ([NA13](#); [Asada et al. 2014](#)). However, such a jet structural study with multiple orders of magnitude in axial distance has been only conducted for M 87 so far.

NGC 6251 is a nearby ($z = 0.025$, [Wegner et al. 2003](#)) giant elliptical galaxy, which has an exceptionally straight and long jet (3 Mpc in projection, [Waggett et al. 1977](#)), and therefore serves as one of the best targets for structural studies of AGN jets. Its kpc-scaled radio emission has been investigated in great detail using the Very Large Array (VLA) ([Perley et al. 1984](#)), and the pc-scaled jet emission using VLBI continuously extending to 50 mas ([Jones et al. 1986](#); [Sudou et al. 2000](#); [Jones & Wehrle 2002](#)). The mass of the SMBH is measured to be $M = (6 \pm 2) \times 10^8 M_\odot$ ([Ferrarese & Ford 1999](#)). Taking the distance ($\simeq 103$ Mpc) into account, NGC 6251 provides a viable apparent size (0.50 pc mas^{-1} or $8700 r_s \text{ mas}^{-1}$, where r_s is the Schwarzschild radius,) to examine the jet structure across the gravitational

regimes dominated by both the SMBH and the host galaxy. In this paper, we report a detection of the structural transition of the NGC 6251 jet that is found with the aid of our new European VLBI Network (EVN) images at 1.6 GHz.

The paper is organized as follows. In Section 2, we describe our observations and data used in this work. We show our analysis and result in Section 3. In Section 4, we discuss the location of the transition, the properties of the pressure, and the comparison with M87 in order to understand the origin of the collimation processes. The angular scale used in this paper is obtained with a cosmology of $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.286$, and $\Omega_\Lambda = 0.714$ (Wright 2006).

2. OBSERVATIONS AND DATA REDUCTION

2.1. EVN Data

We conducted EVN observations of NGC 6251 on 2013 March 10 at 1.6 GHz with the Badary, Svetloe, Zelenchukskaya (Russia), Effelsberg (Germany), Jodrell Bank (UK), Medicina, Noto (Italy), Onsala (Sweden), Shanghai, Urumqi (China), Torun (Poland), and Westerbork (Netherlands) stations. Both left, and right circular polarization data were recorded at each station using eight sub-bands of 8 MHz bandwidth and 2-bit sampling. The data were correlated at the JIVE (Joint Institute for VLBI in Europe) correlator.

Data were calibrated following the standard procedures in AIPS. A priori amplitude calibration for each station was derived from the system temperatures measured during each run and the antenna gain curves. Fringe fitting was performed to remove the residual delays and rates by assuming a point source model. After applying the solutions, the data were exported to Difmap and averaged over 12 s in each sub-band. Then the gain phase and amplitude were self-calibrated by the iterative process of CLEAN to obtain the final image. More detailed observational parameters are described in Table 1.

2.2. VLBA Data

Archival Very Long Baseline Array (VLBA) data at 5 GHz are used and calibrated in the same manner as the EVN data. Also, 12 epochs of the VLBA data at 15 GHz are obtained from the MOJAVE database (Lister et al. 2009). Observations were conducted during 1998–2013. We reproduce all images in agreement with the MOJAVE database. In order to perform a joint analysis, images of the 12 epochs are convolved with the same circular beam with Full Width Half Maximum (FWHM) of 0.54 mas (see more details in Table 1).

2.3. VLA Data

We also use a published Very Large Array (VLA) image of NGC 6251 at 1.4 GHz to compare with the VLBI measurements in Section 4.1. The image, as well as the calibration processes, is shown in Sambruna et al. (2004). Observations were conducted on 1995 August 15 using the full VLA in its A-configuration. The beam is restored to be circular with an FWHM of $2''$.

3. ANALYSIS AND RESULTS

3.1. New EVN Images

Figure 1 shows high dynamic range images of NGC 6251 taken with our EVN observations at 1.6 GHz, and the archival VLBA data at 5 and 15 GHz; table 1 summarizes the detailed image parameters (e.g., beam size, dynamic range). The EVN images are obtained with different weighting schemes (denoted as EVN-i, -ii and -iii) to enhance the sensitivity of the emission at various angular scales. The brightest component at the eastern edge of the object is presumably the core, and a continuous jet emission extends towards the northwest. The jet direction and the knotty features are consistent with each other in all images. This is the first time to see the jet emission associated with NGC 6251 is continuously detected at a distance range of 50 – 150 mas away from the core.

3.2. Derivation of Jet Radius

To investigate the collimation profile of the jet, we derive the radius (half width) of the jet emission along the jet axis in each image. We mainly adopt the methodology of AN12 as follows; in addition, the change of the jet direction in different length scales (i.e., jet bending) is taken into consideration:

1. The position angles (PA) of the jet direction is determined by the averaged PAs of all CLEAN components excluding the core region, weighted by their flux density.
2. The cross sections of the jet are fitted with a single Gaussian function of FWHM Φ_0 at every 1/5 of the beam size (as independent measurements, the resolution limit was studied by Lobanov 2005) along the jet axis to evaluate the transverse structure.
3. The jet radius r (i.e., half of the jet width) is thus defined as half the FWHM of the resultant fitted Gaussian which is deconvolved from the beam FWHM Φ_b taking into account the beam orientation, i.e., $2r = \sqrt{\Phi_0^2 - \Phi_b^2}$, (see also Perley et al. 1984, Sec. IV - d).
4. The uncertainty is estimated from the Gaussian fitting error (in step 2), and the imaging error that is evaluated as:

- 4.1. The dispersion (standard deviation) of the 12-epoch measurements for the VLBA data at 15 GHz.
- 4.2. $\Phi_b/5$ for the other frequencies due to the lack of enough independent observations. Particularly for the EVN data, the jet radii are further averaged over both polarizations (i.e., RR and LL).

The measurements are presented in a machine readable format in Table 2. In our analysis, the jet PA mildly decreases as the length scale increases, ranging from $294^\circ - 298^\circ$ (see also Table 1), which is similarly detected by Jones & Wehrle (2002). All jet cross sections are well represented with a single Gaussian component.

To properly evaluate the uncertainty, we utilized the multi-epoch VLBA data at 15 GHz. The jet radii derived in 12 epochs are in good agreement with each other so that we obtain the standard deviation ($\sigma_{r,15}$) of the jet radii as the imaging error. We estimated the distribution of $\sigma_{r,15}$ as a function of signal-to-noise ratio (SNR), and found it to be well described by a power-law function, $\sigma_{r,15}/\Phi_b = (0.66 \pm 0.09) \times SNR^{-0.68 \pm 0.05}$. The $\sigma_{r,15}$ is about 0.01 mas at the innermost jet region where the $SNR \simeq 200$, while 0.1 mas at the jet downstream where the $SNR \simeq 5$, corresponding to $1/50$ and $1/5$ of the beam size, respectively. Therefore, we consider the upper limit of the imaging error to be $\Phi_b/5$ as the jet radii are measured where the jet is detected when the $SNR \geq 5$ (see also Homan et al. 2002, Appendix A for similar analysis). Note that we assume the time variability of the jet radius is negligible.

3.3. Radius Profile of the Jet

Figure 2 shows the distribution of jet radius (r) as a function of the de-projected distance to the core (z), which we refer to as the radius profile of the jet. The jet viewing angle (θ) for de-projection is uncertain within an upper limit of 47° (Jones & Wehrle 2002). We adopt $\theta = 19^\circ$ derived from a detection of a sub-pc scale counter-jet (Sudou et al. 2000). An independent spectral energy distribution (SED) model suggests a consistent result of $\theta \simeq 18^\circ$ (Chiaberge et al. 2003). Hereafter, we use the de-projected length scale ($27000 r_s \text{ mas}^{-1}$) along the jet throughout the rest of the paper. Note that the jet radius, as defined perpendicular to the jet axis, is not affected by projection effects.

3.4. Collimation Profile by Power-Law Models

Collimation profiles are generally described by power-law functions with some local features, as a manifestation of the global evolution of jet structure. We perform regression analyses with single and double power-law models throughout the whole VLBI dataset and show

the results and their relative residuals in Figure 2. Note that the power-law indices, a , are defined as $r \propto z^{1/a}$ throughout the paper.

First, we fit the data with a single power-law model, r_{SP} ,

$$r_{SP}(z) = A_0 z^{1/a}, \quad (1)$$

which gives the best fit using a power-law index of $a = 1.25 \pm 0.03$, with a $\chi^2/dof \simeq 0.98$ (see also Table 3). The radius profile can be described well with this power-law in the range of $z = (10^5 - 10^6) r_s$, however, it systematically deviates at each end.

Then, we test a double power-law model, in the form of the broken power-law function, r_{DP} ,

$$r_{DP}(z) = r_0 \left[\left(\frac{z}{z_0} \right)^{n/a_u} + \left(\frac{z}{z_0} \right)^{n/a_d} \right]^{1/n}, \quad (2)$$

so that we can simultaneously solve for a_u , a_d , z_0 and r_0 , which are the upstream and downstream power-law indices (pre- and post-break), the break position, and the jet radius at the break position, respectively, and n is a controlling parameter for the sharpness of the break, i.e., the sharper break, the larger n . The radius profile is best fitted with the model parameters listed in Table 3, with χ^2/dof 's $\simeq 0.57 - 0.58$ by adopting different $n \geq 1$.

Note that the different values of sharpness (i.e., choices between n) result in changes of the best fitted parameters (see also Table 3). Particularly, a small value of $n \gtrsim 1$ implies a smooth transition with a significant amount of data located amid the two pure power-law branches, causing an increase of the uncertainty for both a_u and z_0 . However, the resultant fittings are all fairly consistent (in 1σ , and 2σ for $n = 1$ and 2 cases) with power-law indices $a_u \geq 2$ and $a_d = 0.9 - 1$, and the distance of the transition (break position) $z_0 = (1 - 2) \times 10^5 r_s$ regardless of the sharpness. In addition, their relative residuals are uniformly distributed in all distance scales. The oscillatory pattern in the radius profile presumably corresponding to a local enhancement of the emissivity, potentially affects the quantification of the power-law index of the upstream. In order to have a better constraint, it is important to extend the jet structural studies towards the inner regions. Future (sub-)mm VLBI observations, with unprecedented angular resolution, are expected to provide a unique chance to unveil the initial point of collimation and even the genesis of AGN jets.

Next, we perform a statistical test (an f-test) to check if the double power-law model is necessary. Given the f-ratio of 1.71 (i.e., the ratio of χ^2/dof) with the degrees of freedom of the single and double power-law fitting, $dof = 189$ and 187 , respectively, the null hypothesis that the two models fit the population of the data equally well corresponds to a small probability $p \sim 1.4 \times 10^{-4}$. As a

result, the double power-law model is significantly better than the single power-law to describe the radius profile of the NGC 6251 jet. Also, this is further supported by the measurements in both the outer and inner region taken with the VLA and VLBI core data (see Section 4.1).

In summary, we conclude that the structure of the NGC 6251 jet is described by a parabolic shape ($a \simeq 2$) upstream, a conical expansion ($a \simeq 1$) downstream, and the structural transition takes place at a characteristic distance scale of $(1 - 2) \times 10^5 r_s$. The NGC 6251 jet is the second observational evidence of the structural transition from parabolic to conical shape occurring at a scale of $10^5 r_s$ in AGN jet systems, following the result of M 87 (AN12).

4. DISCUSSION

4.1. Supporting Evidence of the Structural Transition

We take a step further to investigate the jet structure beyond the two distance ends, which are shown as the gray data points in Figure 2. The radius profile on kpc scales are derived from an archival VLA image (as introduced in Section 2.3), which was similarly measured by Perley et al. (1984, Fig. 10). Figure 2 shows their innermost portion (with distances $z \leq 20$ kpc) to guide the comparison, which is smoothly connected to the radius profile predicted by the double power-law model, while largely deviated from the single power-law model. The VLA measurements additionally support that the VLBI jet downstream is better described by a conical shape ($a_d \sim 1$) which propagates three orders of magnitude in distance, if the jet structure is indeed linked together on the intermediate scales ($z = 10^6 - 10^8 r_s$). Note that the VLA data are not included in the previous regression analysis. To study the missing link of the jet structure requires facilities with an adequate angular resolution (e.g., VLA, MERLIN), which will be investigated in future work.

On the other side, VLBI cores are considered as the innermost jet emissions, originally suggested by Blandford & Königl (1979). The frequency dependent core-shift ($\Delta_z \propto \nu^{-1}$) due to synchrotron self-absorption enables us to estimate the exact location of the innermost components with respect to the black hole, and hence the innermost jet structure and its width. This technique has been previously demonstrated in M 87 (e.g., Hada et al. 2011, 2013, NA13). In NGC 6251, the core-shift between 15 and 5 GHz was estimated to be $\Delta_z \simeq 0.3$ mas by image registration with the optically thin jet (Sudou et al. 2000). Together with the transverse widths (FWHM, deconvolved from the beam) of the cores, the sub-pc-scaled jet radii can be estimated by the VLBA and EVN cores (see also Figure 2). Once again, they

are relatively consistent with the upstream that is predicted by the double power-law model rather than the single power-law. As a result, we expect that the jet maintains a parabolic shape for at least two orders of magnitude in distance. Interestingly, the power-law index of the jet upstream ($a_u \sim 2$) is very close to the genuinely parabolic field configuration in which the jet extracts electromagnetic energy from a spinning black hole (Blandford & Znajek 1977). The core-shift measurements of NGC 6251 at higher frequencies (i.e., sub-mm bands) can be very helpful to understand the jet formation process as well as to extend the structural study.

4.2. Location of the Structural Transition

We consider the gravitational potential of the NGC 6251 environment: the SMBH and the host galaxy. As indicated in Figure 2, it is found that the structural transition is close to the boundary of the sphere of gravitational influence (SGI, $r_{SGI} \simeq 5 \times 10^5 r_s$) in order of magnitude, where the central SMBH dominates the gravitational potential. SGI is defined as $r_{SGI} = GM/\sigma_v^2$ under the assumption that the stellar distribution is random-motion supported rather than rotationally, where σ_v is the velocity dispersion of the collective stars, i.e., the elliptical galaxy here (Peebles 1972). In NGC 6251, it is measured by optical spectroscopy that $\sigma_v \simeq (290 \pm 14)$ km s⁻¹ in the galaxy and the ratio of rotational velocity to velocity dispersion $v/\sigma_v = 0.16$ (Ferrarese & Ford 1999; Kormendy & Ho 2013), which gives our estimates of the r_{SGI} above. The estimated SGI can be an upper limit, since one may expect much larger σ_v towards the nuclei of NGC 6251, for we cannot spatially resolve the region at present. Note that the evaluation of the SGI may be affected by the triaxiality of the bulge, or the warped disk structure in the nucleus possibly due to galaxy merging, as discussed in Ferrarese & Ford (1999). A study of the stellar velocity structure with an angular resolution ~ 10 mas will be helpful to narrow down this issue. However, we believe that both effects are insignificant in order of magnitude estimates. Approximately, the cool core is expected to be thermodynamically stable, so that virial equilibrium is considered for the gas as well as for the stars. As a consequence, the Bondi radius ($r_B = 2GM/c_s^2$, where c_s is the local sound speed) is expected to be close to the SGI. For instance, M 87, which is the very limited case we can directly compare those two numbers thanks to its proximity, the Bondi radius is indeed close to the SGI ($r_B \simeq 3.8 \times 10^5 r_s$, AN12 and the references therein, and $r_{SGI} \simeq 3.1 \times 10^5 r_s$ with $\sigma_v \simeq 380$ km s⁻¹, Murphy et al. 2014; we adopt a SMBH mass of $6.6 \times 10^9 M_\odot$ Gebhardt et al. 2011.)

Therefore, the Bondi radius in NGC 6251 is expected

to be a few $10^5 r_s$ with a virial temperature $k_B T_{vir} \simeq \mu m_p \sigma_v^2 \simeq 0.5 \text{ keV}$ derived from the velocity dispersion, where μ ($\simeq 0.6$) and m_p are mean molecular weight and proton mass. Independently, we estimate $c_s = \sqrt{\gamma p / \rho} = \sqrt{\gamma k_B T / m_p} \simeq 500 \text{ km s}^{-1}$ with an upper limit of temperature $kT \simeq 1.6 \text{ keV}$, which is extrapolated from X-ray observation on a scale of 20 kpc (or $10''$, Sambruna et al. 2004), where γ ($= 5/3$), p , and ρ are adiabatic index, pressure, and density of the gas. This estimation gives a lower limit of the Bondi radius to be $r_B \simeq 4 \times 10^5 r_s$ and well agrees with the former expectation. Note that the extrapolation is made towards the Bondi radius assuming a flat temperature profile, which was demonstrated in many simulations that the profile is nearly flat in a cool core of elliptical galaxies (e.g., Gaspari et al. 2012, 2013).

We compare the collimation (radius) profile of the jet in NGC 6251 to that in M 87, as the structural transition of the M 87 jet is also located at around the Bondi radius (AN12). Figure 3 shows their jet radii and de-projected distances respectively normalized by their Schwarzschild radii. Located in the same type of galaxy, the two jets show remarkably similar structures. They both undergo a structural transition at a scale of $10^5 r_s$, suggesting an interplay with the galactic environment, i.e., the SMBH and its host galaxy. The collimation process of AGN jets may be fundamentally characterized by external galactic medium, which has been argued that the stratified ISM is responsible (AN12; NA13). Recently, it has also been shown that the jet can be confined by the wind generated from the accretion flow within the Bondi radius (Yuan et al. 2015; Globus & Levinson 2016).

4.3. Pressure Estimates from Synchrotron Minimum Energy Assumption

The jet internal pressure is estimated to be compared with the external medium. We consider the NGC 6251 jet a relativistic system organized by helical magnetic field, i.e., the toroidal component of the field (denoted by B_ϕ in the observer's frame, and $B'_\phi = B_\phi / \Gamma$ in the fluid comoving frame, where Γ is the bulk Lorentz factor) is dominant farther from the black hole.

Assuming the jet satisfies the synchrotron minimum energy condition (Pacholczyk 1970), the magnetic field strength B_ϕ is estimated as

$$B_{eq} = [6\pi(1+k)c_{12}(\alpha, \nu_{min}, \nu_{max})L_{syn}(\alpha, \nu_{min}, \nu_{max}) / (\Phi V)]^{2/7} \quad (3)$$

(equivalently, the internal pressure $p_{eq} \simeq B_{eq}^2 / 8\pi$) by using the radio emissivity along the jet. First, we adopt a spectral index $\alpha \simeq 0.6$ ($S_\nu \propto \nu^{-\alpha}$) that has been found in both the kpc- and pc-scaled (optically thin) jet (Perley et al. 1984; Jones & Wehrle 2002), and a nominal frequency integrand of $10 - 10^5 \text{ MHz}$ to estimate the

synchrotron luminosity L_{syn} , as well as to determine the factor c_{12} ; we set the proton-to-electron energy ratio $k = 1$ as a strict minimum; the emitting volume ΦV is estimated with a filling factor $\Phi = 1$ and a circular jet cross-section characterized by the jet radius, which is derived in Section 3. Second, we estimate the bulk Lorentz factor Γ by adopting an empirical correlation $\Gamma \theta_j \simeq 0.2$ with the half opening angle $\theta_j = \tan^{-1}(r/z)$, which has been found in large samples of AGN jets (Jorstad et al. 2005; Pushkarev et al. 2009; Clausen-Brown et al. 2013). This relation is also demonstrated in the MHD models, indicating a causally connected jet in the acceleration zone (e.g., Tchekhovskoy et al. 2009; Komissarov et al. 2009; Pu et al. 2015). As a result, Figure 4 shows the field strength ($B'_{eq} = B_{eq} / \Gamma$) together with the jet pressure ($p'_{eq} = B_{eq}^2 / 8\pi$) in the fluid frame. Note that true minimum-energy field strength can be one order of magnitude higher than the strict lower limit by tuning the parameters mentioned above.

4.3.1. The Parabolic Jet

To maintain a parabolic jet ($a \simeq 2$) in the upstream, pressure matching is expected between the jet boundary and the external ISM ($p'_{jet} \simeq p_{ext}$). Analytical and numerical models have shown that the magnetized jet can be genuinely parabolic when the ISM pressure has a profile of $p_{ext} \propto z^{-b}$, $b = 2$ (Zakamska et al. 2008; Komissarov et al. 2009), as the black dotted line plotted in Figure 4. Interestingly, this is consistent with the estimated minimum-energy jet pressure profile, if there is no significant change in the synchrotron parameters. In addition, at the structural transition, the estimated jet pressure $p'_{jet} \sim$ a few $10^{-9} \text{ dyn cm}^{-2}$ is in agreement with the external ISM pressure at the SGI (or, the Bondi radius) $p_{ext} = n_e k_B T \simeq 10^{-10} - 10^{-8} \text{ dyn cm}^{-2}$, where we adopt a nominal range of electron number density in typical radio galaxies $n_e = 0.1 - 10 \text{ cm}^{-3}$ (Fujita et al. 2014). As a result, it is reasonable to believe that the external pressure of the parabolic jet has a profile of $b \simeq 2$, which is consistent with Radiative Inefficient Accretion Flow (RIAF) models ($1.5 \leq b \leq 2.5$, NA13 and the references therein). Similar discussions can be referred to in AN12 and NA13. Note the accretion type of the SMBH in NGC 6251 remains a matter of debate: RIAF or standard accretion disk. Ho (1999) suggested that an Advection-Dominated Accretion Flow (ADAF, a subtype of RIAF) is present in the nucleus of NGC 6251 based on the radio-to-X-ray SED. On the other hand, the X-ray spectral properties are in favor of the presence of a standard accretion disk (Gliozzi et al. 2004). Our result supports RIAF to be the accretion type in NGC 6251.

4.3.2. The Conical Jet

Beyond the structural transition, the jet changes its structure in a conical shape ($a \simeq 1$). We consider two scenarios to form a conical jet regarding the pressure properties at the structural transition, which we call a sharp transition ($p'_{jet} > p_{ext}$) and a smooth transition ($p'_{jet} \simeq p_{ext}$).

A sharp transition is that the jet becomes over-pressured with respect to the external pressure at the transition while it undergoes an over-collimation (due to a compression shock) and turns into conical shape. In the case of M87, the knot complex (HST-1), which is located at the structural transition in the M87 jet, is likely caused by an imbalance between p'_{jet} and p_{ext} (AN12 and the reference therein). As Figure 4 shows, p_{ext} is nearly a constant in the conical jet regime as suggested by the estimation on the SGI and by X-ray measurements (Evans et al. 2005), which is expected in the galactic environment beyond the SGI. It has been shown by Clarke et al. (1986) in an MHD simulation that an over-pressured jet can be conically expanding in a flat external medium. However, it remains unclear whether the jet is over-pressured because the lower limit of the minimum-energy jet pressure is comparable to the external pressure. We note that Γ (or, the jet speed) is one of the important parameters, where it is assumed following $\Gamma \theta_j \simeq 0.2$, i.e., no deceleration in the conical jet. In the case of M87, the jet has also shown to have a peak apparent speed at the transition (Asada et al. 2014). It is interesting that the kpc-scaled pressure estimates of NGC 6251 show a significant difference between the estimated jet pressure (given by the VLA measurements) and the external pressure, which can be compensated if we take the deceleration into account. Meanwhile, a transition of the jet pressure will be expected around the structural transition, and then an over-pressured jet ($p'_{jet} > p_{ext}$) can be explained.

Nevertheless, in the structure of the NGC 6251 jet, we currently see neither a sudden decrease of the jet radius (i.e., over-collimation), nor an isolated prominent knot as a counterpart of HST-1 in the M87 jet so far, while there is a jagged shape in the radius profile near the SGI ($z \simeq 50$ pc). It is noteworthy that proper motion studies reported by MOJAVE program show several knotty features moving in subluminal apparent speeds $\beta_{app} \lesssim 0.1$ (Lister et al. 2013). Time variability may explain the current absence of such a knotty feature (HST-1 is also time varying, Cheung et al. 2007; Hada et al. 2014) and an over-collimated region at the SGI as well as the apparent jagged shape. Further monitoring observation with EVN and observations with higher angular resolution across the transverse direction is important to unveil the true structure of the jet, and to measure the bulk Lorentz factor Γ . A polarization imaging may be helpful in probing this transition and the nature of the

stationary knot. We also suggest that a similar analysis can be applied to M87 in order to constrain the jet pressure of the conical expansion beyond the transition.

We may also consider a smooth transition: the condition of pressure matching is kept on the jet boundary ($p'_{jet} \simeq p_{ext}$) with the smooth structural transition. In addition to the smooth structural transition (i.e., no over-collimation), Figure 4 shows that the lower limit of the minimum-energy jet pressure seems to connect with the external pressure. Zakamska et al. (2008) shows that an MHD jet maintains a conical shape under the condition that the external pressure with a drastically dropping profile $b = 4$ in the constant jet speed regime. It would be, however, difficult to meet this condition as we described in Figure 4, the external pressure is nearly a constant in the conical jet regime as suggested by the estimation on the SGI and by X-ray measurements. In order to keep the conical (expanding) structure of the jet with the condition of pressure matching to the flat external pressure profile, in-situ energy dissipation is needed to sustain the jet internal pressure p_{jet} as constant. One of the possibilities would be the conversion from the bulk kinetic energy to the jet internal energy. Indeed, Laing & Bridle (2002) suggests a gradual and substantial deceleration of the jet velocity located at 1–3 kpc from the central engine for the FR I type jets based on the VLA polarimetric observations. It is interesting to measure the velocity structure of the conical jet. We also note that the magnetic reconnection can be another possible origin for the in-situ energy dissipation, and future monitoring observation at this region will detect the local time variability associated with this event. Therefore, further observations towards the NGC 6251 jet is needed to explore the physical origin of the AGN jet structural transition.

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Facilities: EVN, VLA, VLBA

Software: AIPS, Difmap

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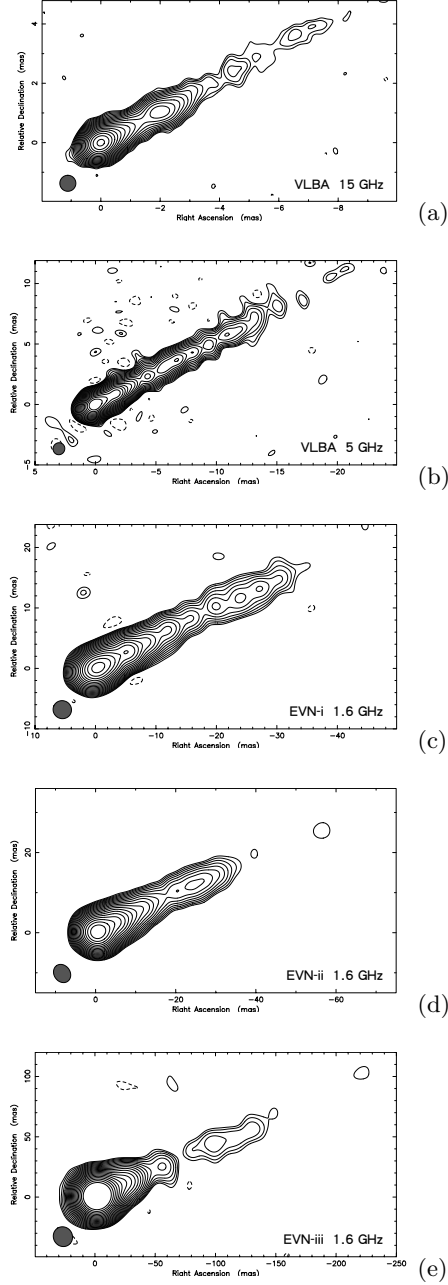


Figure 1. Radio images of the NGC 6251 jet in different length scales. From top to bottom, they are taken with: (a) VLBA at 15 GHz (1998 Jun 02), (b) VLBA at 5 GHz, (c) EVN at 1.6 GHz with uniform weight (EVN-i), (d) EVN at 1.6 GHz with natural weight (EVN-ii), (e) EVN at 1.6 GHz with natural weight and tapering (EVN-iii). The synthesized beam is shown at the bottom left corner of each image. Contours are plotted at $(-1, 1, \sqrt{2}, 2, \dots) \times 3\sigma$, where σ is the residual rms noise. See the values of σ and the beam sizes in Table 1. Note that the intrinsic jet radius (or width) is obtained by deconvolution from the beam, which is not directly illustrated from the contour level.

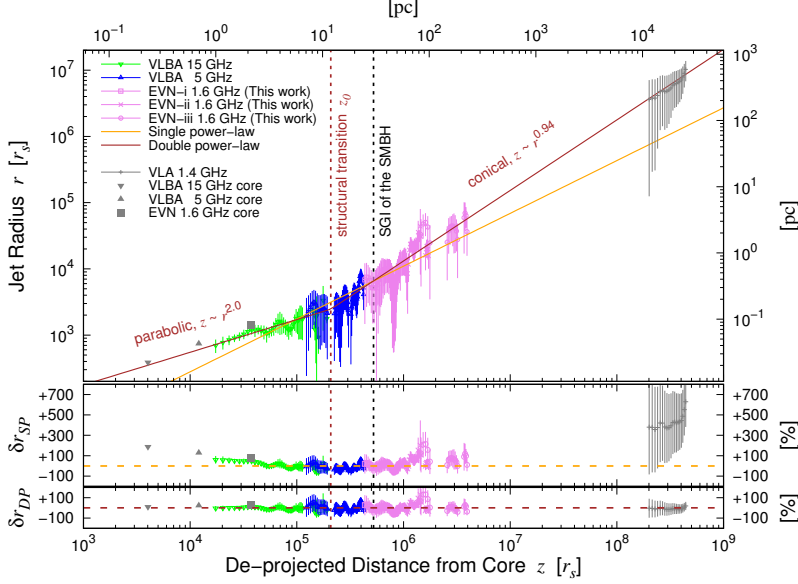


Figure 2. Top panel: The radius profile of the NGC 6251 jet in units of Schwarzschild radius (r_s) and pc, using archival VLBA data at 15 and 5 GHz (green and blue triangle), and our EVN(-i, ii, iii) data at 1.6 GHz with three weighting schemes (violet square, cross, and circle). Towards the profile are fitted the single (orange solid line), and double power-law models (brown solid line), where we show the case of the sharpness parameter $n = 100$ here. Statistics (f-test) manifests that the data are better fitted by double power-law models (with all n) than by a single power-law (see also Section 3). Furthermore, the double power-law model is also supported by the VLA data (gray plus signs) and VLBI cores (gray triangles and squares), as discussed in Section 4.1. Note that the VLA data and VLBI cores are not included in the regression analysis.

Middle and bottom panels: The relative residuals of the jet radii for the single ($\delta r_{SP} = r/r_{SP} - 1$) and double power-law models ($\delta r_{DP} = r/r_{DP} - 1$; $n = 100$). The single power-law shows a systematic deviation at the two distance ends, while the double power-laws (i.e., for all n) show uniformly distributed relative residuals in all distance scales.

We conclude that the jet structure is described by a parabolic shape upstream ($z \propto r^a$, $a \simeq 2$) and a conical shape downstream ($a \simeq 1$) with a transition located at a characteristic distance $z_0 = (1 - 2) \times 10^5 r_s$ (brown dash line), which is fairly close to the sphere of gravitational influence (SGI) of the SMBH ($r_{SGI} \simeq 5 \times 10^5 r_s$, black dash line) in order of magnitude.

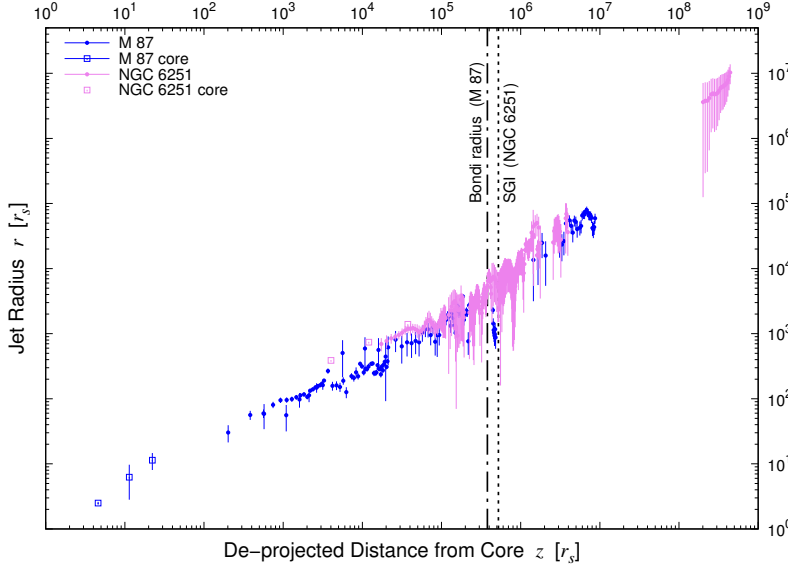


Figure 3. Combined radius profiles of the jets in NGC 6251 and M 87, with their jet radii and de-projected distances normalized by their Schwarzschild radii (r_s). The detailed description of the measurements can be found in Figure 2, AN12 and NA13. Likewise, M87 shows a parabolic shape ($z \propto r^a$, $a \simeq 1.7$) in the upstream, a conical shape ($a \simeq 1$) in the downstream, and a structural transition in a few $10^5 r_s$, corresponding to the Bondi radius of M87 $r_B \simeq 3.8 \times 10^5 r_s$ (dot-dashed line), while the SGI of NGC 6251 is $r_{SGI} \simeq 5 \times 10^5 r_s$ (dashed line). The similarities of the two jet structures suggest that the collimation process of AGN jets is fundamentally characterized by their external galactic medium, which is gravitationally controlled by the SMBH and its host galaxy.

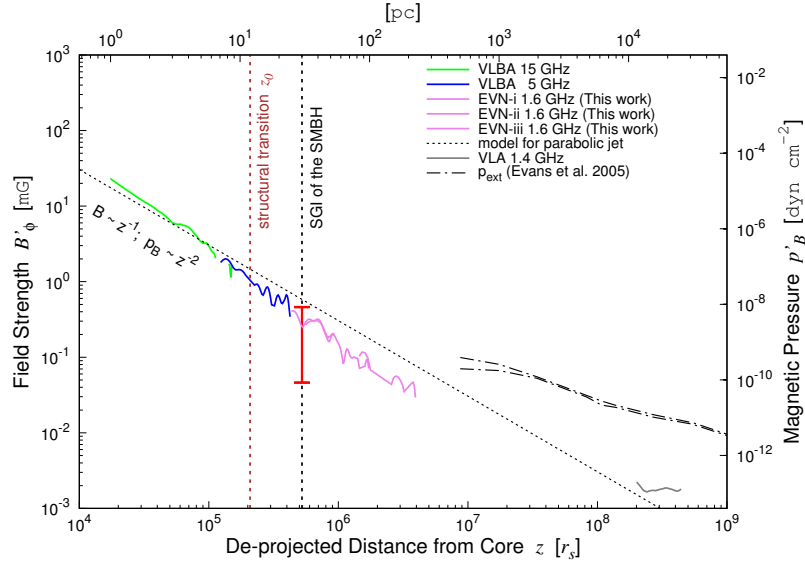


Figure 4. Distribution of the lower limit of the (fluid frame) magnetic field strength B'_{eq} and the equivalent magnetic pressure $p'_{eq} = B'^2_{eq}/8\pi$ of the NGC 6251 jet as a function of the de-projected distance to the core z . Synchrotron minimum energy condition and an empirical relation $\Gamma\theta_j = 0.2$ (Clausen-Brown et al. 2013) are assumed, where θ_j is the intrinsic half opening angle. The vertical dashed lines are as defined in Figure 2. The dotted line illustrates the theoretical profile of the external pressure $p_{ext} \propto z^{-b}$, $b = 2$ for a parabolic MHD jet (Zakamska et al. 2008; Komissarov et al. 2009). The red line segment indicates the range of the external ISM pressure at the SGI, $p_{ext} = n_e k_B T \simeq (10^{-10} - 10^{-8}) \text{ dyn cm}^{-2}$, with a nominal range of electron number density in typical radio galaxies $n_e = 0.1 - 10$ (Fujita et al. 2014). The two dash-dotted lines represent the $1-\sigma$ uncertainties of the external gas pressure p_{ext} by X-ray observation (Evans et al. 2005). See Section 4.3 for more discussions.

Table 1. Image Parameters

Facility	Code	Epoch (yyyy-mm-dd)	Frequency (GHz)	Beam FWHM (mas \times mas, $^\circ$)	RMS noise (μ Jy/Beam)	Dynamic range	Jet PA ($^\circ$)	Φ_b^1 (mas)
EVN-i ²	ET028	2013-03-10	1.658	$3.06 \times 2.96, 65.1^\circ$	127	1874	295.9	3.02
EVN-ii ²	ET028	2013-03-10	1.658	$4.81 \times 4.01, 35.6^\circ$	51	5392	295.9	4.78
EVN-iii ²	ET028	2013-03-10	1.658	$16.7 \times 15.8, 33.7^\circ$	54	7740	294.6	16.78
VLBA	V105	1998-04-30	4.816	$0.997 \times 0.962, -24.1^\circ$	63	3460	297.9	0.975
MOJAVE data								
VLBA	BT036	1998-06-02	15.365	$0.450 \times 0.390, -25.8^\circ$	204	1701	298.4	0.54 ³
VLBA	BJ033B	2000-05-30	15.363	$0.468 \times 0.453, 25.6^\circ$	454	844	298.4	0.54
VLBA	BS089	2001-02-28	15.365	$0.346 \times 0.326, 34.1^\circ$	370	630	298.4	0.54
VLBA	BL137R	2007-01-06	15.365	$0.564 \times 0.468, -42.8^\circ$	967	487	298.4	0.54
VLBA	BL149AA	2007-06-03	15.365	$0.528 \times 0.500, 33.7^\circ$	863	532	298.4	0.54
VLBA	BL149AF	2007-08-16	15.365	$0.557 \times 0.481, 89.7^\circ$	675	717	298.4	0.54
VLBA	BL149AK	2008-07-17	15.365	$0.506 \times 0.494, -42.9^\circ$	547	863	298.4	0.54
VLBA	BL149BF	2008-11-26	15.357	$0.543 \times 0.483, -18.3^\circ$	657	686	298.4	0.54
VLBA	BL149BM	2009-06-03	15.357	$0.524 \times 0.496, 63.3^\circ$	585	785	298.4	0.54
VLBA	BL149CL	2010-07-12	15.357	$0.496 \times 0.482, -41.4^\circ$	390	1167	298.4	0.54
VLBA	BL178AO	2012-09-02	15.357	$0.552 \times 0.486, -6.18^\circ$	495	715	298.4	0.54
VLBA	BL178BH	2013-08-12	15.357	$0.527 \times 0.461, -25.2^\circ$	470	802	298.4	0.54

¹ Φ_b : Beam FWHM perpendicular to the local jet axis.

²Weighting schemes of EVN-i, -ii, and -iii images are uniform, natural, and natural with tapering, respectively.

³MOJAVE images are convolved with the same circular beam of 0.54 mas in the analysis.

Table 2. Measurements of the Jet Radii and Estimated Uncertainties

z (mas)	Φ_0 (mas)	$e_{\Phi_0, fit}$ (mas)	r (mas)	$e_{r, fit}$ (mas)	e_r (mas)
EVN-i, 1.6 GHz, RR pol.					
16.2	3.73	0.05	1.09	0.04	0.61
16.8	3.74	0.05	1.11	0.04	0.61
17.4	3.62	0.05	1.00	0.04	0.61
18.0	3.47	0.04	0.85	0.04	0.61
18.6	3.34	0.04	0.71	0.05	0.61

NOTE— This table is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content. z : deprojected axial distance. Φ_0 : fitted Gaussian FWHM of the jet cross section. $e_{\Phi_0, fit}$: fitting uncertainties of Φ_0 . r : jet radius. $e_{r, fit}$: fitting uncertainties of r . e_r : uncertainties of r taking the imaging error into account, which is described in Section 3.

Table 3. Best Fit Parameters of the Power-Law Models

a or a_u	A_0 ($r_s^{1-1/a}$)	a_d	z_0 ($10^5 r_s$)	r_0 ($10^3 r_s$)	n	χ^2/dof
Single power-law, Equation (1)						
1.25 ± 0.03	0.18 ± 0.05	—	—	—	—	0.98
Double/Broken power-law, Equation (2)						
6.6 ± 6.0	—	0.83 ± 0.06	1.3 ± 0.7	1.0 ± 0.4	1	0.58
3.0 ± 0.7	—	0.88 ± 0.05	1.7 ± 0.5	1.6 ± 0.4	2	0.57
2.5 ± 0.4	—	0.90 ± 0.04	1.8 ± 0.5	1.9 ± 0.4	3	0.57
2.3 ± 0.3	—	0.91 ± 0.04	1.9 ± 0.4	2.1 ± 0.3	4	0.57
2.2 ± 0.2	—	0.92 ± 0.04	2.0 ± 0.4	2.2 ± 0.3	5	0.57
2.0 ± 0.1	—	0.94 ± 0.04	2.1 ± 0.3	2.5 ± 0.2	100	0.57

NOTE— a : power-law index of the single power-law model, A_0 : normalization parameter, a_u : upstream power-law index (pre-break) of the double power-law model, a_d : downstream power-law index (post-break), z_0 : deprojected axial distance of the break position, r_0 : jet radius at the break position, n : controlling parameter for the sharpness of the break, and χ^2/dof : reduced chi-square of the fitting.